Development of an fNIRS Equipment for Monitoring Human Brain Activity in the Pre-frontal Region

Submitted By:

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September, 2016

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A thesis submitted in partial fulfillment of the requirement for the degree of Masters of Science

In
Robotics and Intelligent Machines Engineering

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DECLARATION

It is hereby announced that the research has been accomplished for the degree of Masters of Engineering in Robotics and Intelligent Machines. The research work has been completed and it is not copied from any other published work. I thusly likewise announce that no portion of the research work in this thesis has been submitted in backing of an application for another degree in this university or any other institute.

Ehtisham ul Hasan

This thesis is dedicated to my family, supervisor and co-supervisor.

ACKNOWLEDGEMNT

"In the name of Allah the most Merciful and Beneficent"

Firstly thanks and praise to Allah, the Almighty, due to His blessings I am able to complete my thesis successfully.

Special thanks to my family, the ones towards whom expressing gratitude would not be enough, for the overwhelming love and care they present to me. Without their appropriate direction it would have been incomprehensible for me to finish my study. Because of my mother for their consolation warmth, considerations, petitions and giving me genuine happiness at whatever point I am discouraged.

I want to express my profound and sincere appreciation to my supervisor, Dr. Yasar Ayaz, for giving me the chance to work under his watch. His auspicious commitment, support, kindness and profitable advices helped me shape my work into its final structure. My sincere thankfulness goes to my Co supervisor Dr. Noman Naseer for profitable direction and recommendations. Indeed, his input and valuable remarks were truly useful.

I am deeply indebted to my committee members especially to Dr. Yasar Ayaz and Dr. Noman Naseer for their kindness in examining my research work and providing suggestions for improvement and for generously supporting the thesis with their expertise throughout. I'm grateful for their encouragement, advices and for his helpful criticism and comments.

Last but the least, I want to thank all my friends and colleagues who helped me energetically and sincerely, supported me during my worst times and gave me a quiet environment in entire residency of my research work.

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LIST OF ABBREVIATIONS

BCI	Brain Computer Interface
fNIRS	Functional near infrared spectroscopy
HbO	Oxygentaed Hemoglobin
HbR	Deoxygenated Hemoglobin
MBLL	Modified Beer Lambert Law
LDA	Linear Discriminant Analysis
ECoG	Electrocorticography
PET	Positron Emission Tomography
SPECT	Single Photon Emission Computed Tomography
fMRI	Functional Magnetic Resonance Imaging
EEG	Electroenchelography

Abstract

This research presents the development of a cost effective functional near infrared spectroscopy (fNIRS) equipment for monitoring human brain activity in the pre frontal cortex region. Combination of three dual wavelength near infrared LED sources and eight photodiodes form a 12 channel brain activity acquisition module. The two wavelengths 760nm and 850nm are emitted one by one after regular intervals and the acquired data is continuously logged into an excel file. In this design intensities falling onto the photodiodes are fed into the Modified Beer Lambert Law (MBLL). Using this law we observe the behaviour of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) at various instants. Change in concentration of HbO and HbR according to human brain activity is recorded. Feature extraction is performed using heuristic methods and Linear Discriminant Analysis (LDA) has been used to verify, one the appropriateness of selected feature and second the validation of data acquired through the developed fNIRS equipment based on minimum effective criteria of classification accuracy for distinguishing two or more tasks.

CHAPTER 1

Introduction

1.1 Introduction

Brain computer interface (BCI) also termed as a mind-machine interface, a brain-machine interface (BMI), or sometimes a direct neural interface. It is a technology that translates brain-signals into either commands or messages. If the brain signals are translated into commands, they can be used to control external devices, such as, computers, robotic arms etc. However, in case where the brain signals are translated into messages, they can be used to communicate.

In general, brain, the central nervous system sends signal to the peripheral nervous system, spinal cord to perform a task. A brain computer interface on the other hand, by-pass the peripheral nervous system and sends data to a computer / processing unit (microcontroller) where the control commands are computed and generated.

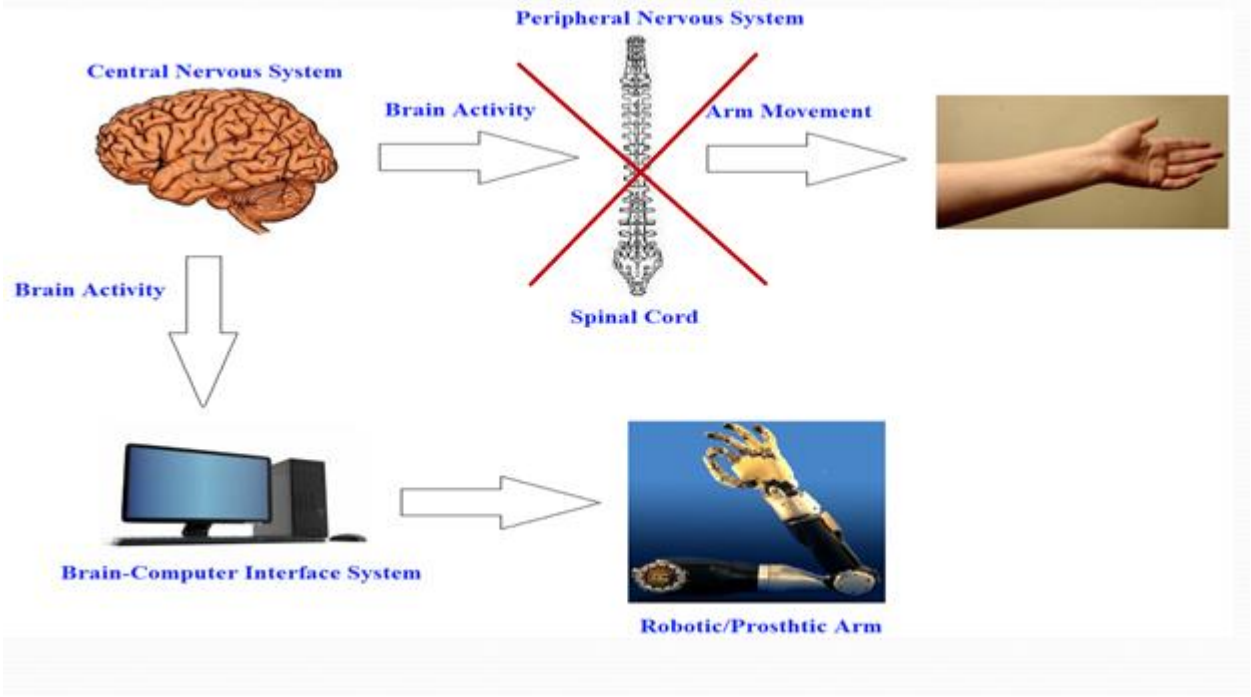

Figure 1.1: Basic overview of a Brain Computer Interface (BCI)

The generation of a control command is done through classification of the brain signal on the basis of specific distinguishable features.

In 1924, Hans Berger was the first one to use electroencephalography (EEG) to record human brain activity.

The classification of the recorded brain signal is the secondary part of a BCI system. The preliminary part is to acquire and log the data of the human brain activity. BCI systems use various methods to record human brain activity. These methods can be categorized into two major domains as shown in figure below:

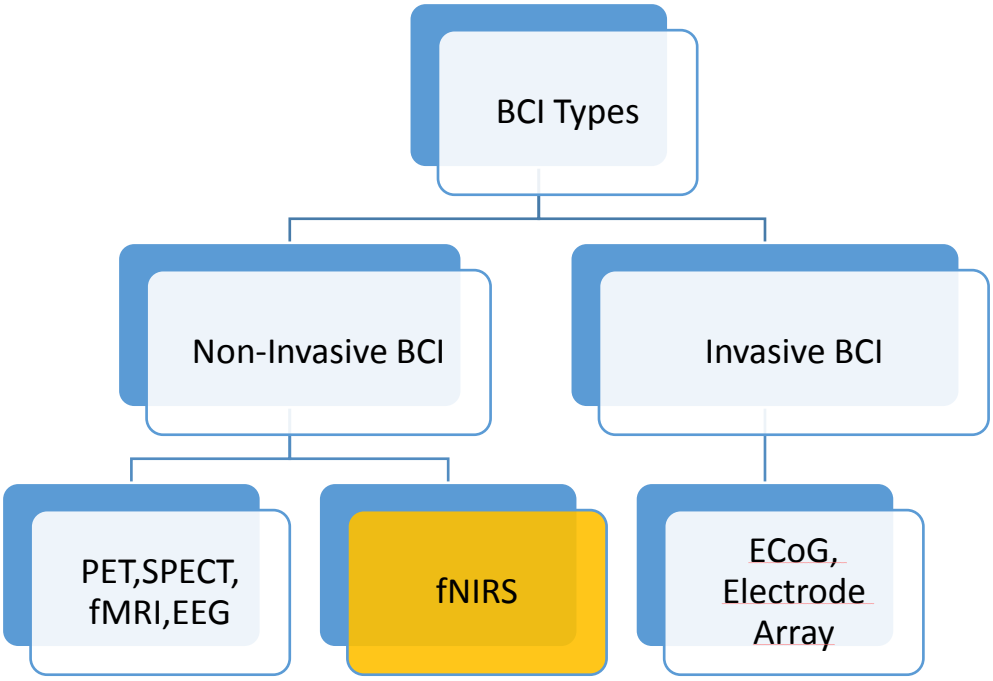

Figure 1.2: BCI systems categorization

Within the invasive and non-invasive categories of BCI systems, a brief overview of each technology is given. In contrast to the working principles, pros and cons of various technologies a comparison of functional near infrared spectroscopy (fNIRS) with its competitive technologies is developed to support the reason of selecting fNIRS on preference.

Invasive BCI involves placement of electrodes inside the skull, into the grey matter of the brain through neurosurgery. There is another treatment that also comes under the invasive BCI is where the electrodes are placed on the skull and not inside the grey matter of the brain and the rest of the system is outside the brain but since the scalp needs to be opened through neurosurgery to reach the skull. Due to a small variation that the acquisition system is placed outside brain, the term partial invasive BCI is often used.

Procedures include:

1) Electrocorticography (ECoG),
2) Placement of electrode array inside brain's grey matter

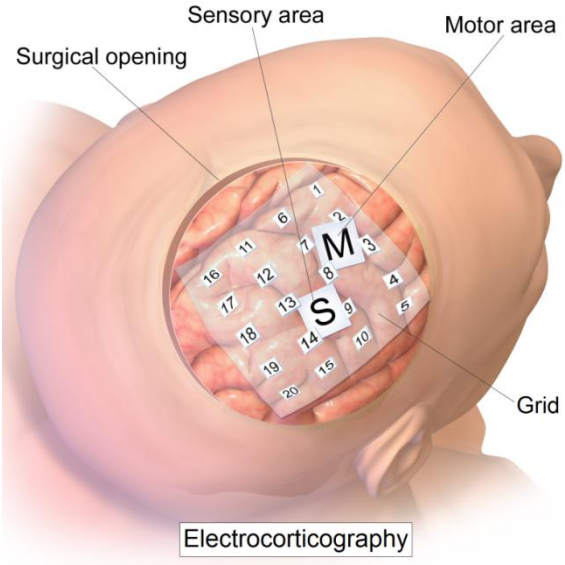

Figure 1.3: Intra-cranial electrode grid for electrocorticography

It would be significant to mention here that each of the two technologies mentioned above involve neurosurgery. Since invasive types of BCI systems involve neurosurgery, people are reluctant to undergo such a procedure even if they are suffering from some major amputation or loss. People don't want to go under any sort of surgery that can put them in state of trauma in addition to their present state of illness.

Moreover, since people know about technology aspect these days, they prefer adopting a non-invasive BCI system. Non-invasive BCI systems are further divided into two sub-fields:

1) Nuclear Brain Imaging Techniques
2) Functional Brain Imaging Techniques

The nuclear brain imaging technology includes positron emission tomography (PET) and single photon emission computed tomography (SPECT) whereas functional magnetic resonance imaging (fMRI) and functional near infrared spectroscopy (fNIRS) fall under the functional brain imaging technology.

Nuclear brain imaging techniques include PET and SPECT. **PET** is **Positron Emission tomography**. The basic principle behind PET is that blood supply and glucose metabolism within a brain region are largely coupled and this technique gives a vivo assessment of brain physiology. It involves the peripheral injection of a radiotracer into a vein, which then travels into the brain and deposits into neurons. Detectors surrounding the brain register photons and measure the metabolism which reflects the rate of cerebral glucose metabolism. As neuronal activity increases, there is an associated increase in blood flow, which supports the oxygen and glucose consumption requirement.

Figure 1.4: Image of a typical positron emission tomography (PET) facility

Similarly, **SPECT** is **single photon emission computed tomography**. It uses a three dimensional distribution of a radiotracer within the human brain to map the cerebral blood flow through a certain neurotransmitter receiver activity.

Figure 1.5: Brain Single Photon Emission Computed Tomography (SPECT) Scan

In these two nuclear brain imaging techniques, the equipment seems somewhat identical but the difference between the two can be seen in the table below

PET	SPECT
Emits Positrons	Emits Gamma Radiations
High Resolution	Low Resolution
High running Cost Scanner	Less Capital Intensive Scanner

Table 1.1 Comparison between PET and SPECT technologies [1]

The figures shown above also explain that a sufficiently large room is required to install equipment related to nuclear brain imaging techniques. Moreover, portability, maintenance and preserving the radio nuclide as per the half life standards require expansive facility to be established along with installation of the equipment.

Therefore, the scope comes down to using functional brain imaging techniques that include fMRI, EEG and fNIRS technology. **Functional magnetic resonance imaging (fMRI)** studies brain functions instead of studying brain as a whole. Different brain regions are specialized to perform different sensory, motor and cognitive functions. Brain regions become more active metabolically when they perform the activity for which they are specified. The increased metabolic activity in "activated" brain regions causes local increases in cerebral blood flow. fMRI localizes these regions during performance of a particular cognitive function using a basic principle called Blood oxygenation level dependent (BOLD) to generate data that can create images because oxygenated and deoxygenated blood have different magnetic properties for different tasks performed.

Figure 1.6: Fully integrated fMRI solution for auditory and visual stimulus presentation, response collection, experiment synchronization and planning

Electroencephalography (EEG) there is another functional brain imaging technique in which the person has to place the EEG electrodes on the forehead using a gel. The spontaneous electrical activity of human brain taking place over intervals of time due to the fluctuating voltage within the brain neurons is recorded. It is sometimes called a brain wave test as it measures the fluctuations and patterns in electrical processes within the brain [2].

Functional Near-Infrared Spectroscopy (**fNIRS**), is the use of near-infrared spectroscopy for the purpose of functional neuro-imaging. The term spectroscopy particularly deals with measurement of dispersed light on interaction with matter. A set of near infrared source and a photodiode for an optode through which spectroscopy is carried out and since the source emits the wavelength of the near infrared region forms the term functional near infrared spectroscopy.

Just as the firing pattern of neurons differ with respect to the type of activity being performed. Similarly, there is a change in the chromophores of the brain hemoglobin against each activity being performed. Since it's not possible to monitor or observe the behaviour of all the chromophores of the brain, the wavelength being thrown by the sources is used to focus onto the chromophores responsible. This can be elaborated from the figure below.

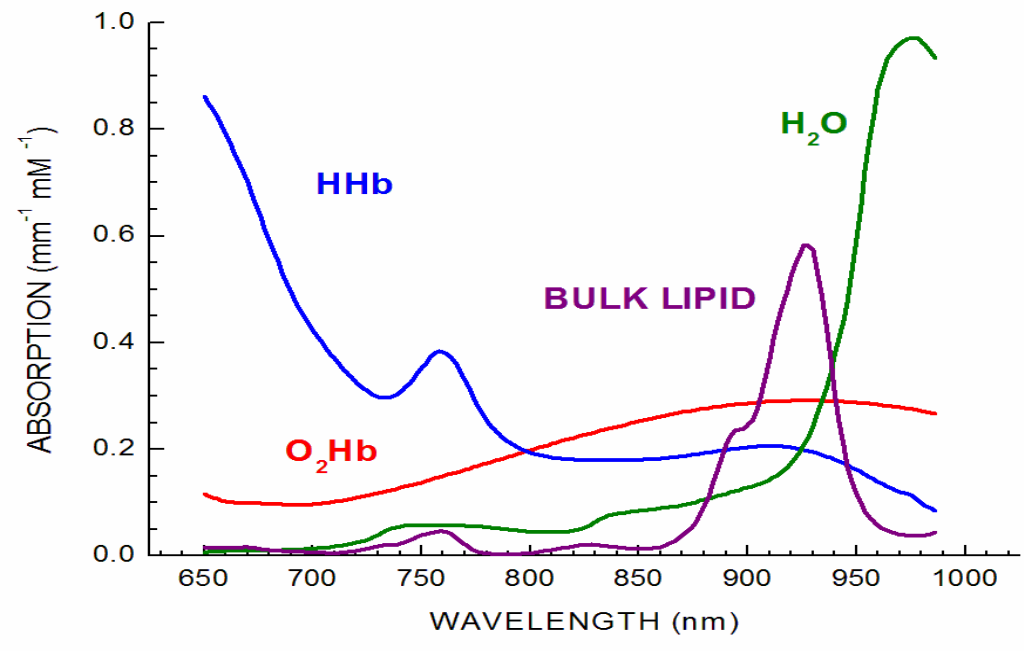

Figure 1.7: Absorption of different brain chromophores in the near infrared range [3]

The figure above shows the level of absorption of near infrared wavelengths by various chromophores of the brain. The range of wavelengths between 650 nm and 860 nm, absorb only two chromophores namely oxygenated hemoglobin (HbO) and the deoxygenated hemoglobin (HbR) also termed as reduced hemoglobin in a relatively significant amount as compared to others. On the basis of number of chromophores responsible for depicting the brain activity the number of wavelengths are determined. Since two chromophores between 650nm and 860nm seem to hold the details of brain activity so a dual wavelength near IR LED is to be used with a detector having a sensitivity range between 600nm and 900nm atleast.

In this technology, the person is supposed to wear a virtual reality device containing a number of emitters and detectors on the forehead. Unlike EEG, no holding gel for optodes or ointment on the forehead is to be applied for acquiring the signals of human brain activity. Moreover, unlike fMRI the system is portable, safe, serviceable and is inexpensive as compared to both EEG and fMRI technology.
In addition to this, following parameters also support the use of fNIRS technology on preference amongst the non-invasive technologies of brain imaging techniques.

Temporal Resolution	Spatial Resolution	Low Cost
EEG	fMRI	fNIRS
fNIRS	fNIRS	EEG
fMRI	EEG	fMRI

Table 1.2: Comparison between various techniques comparable to fNIRS [3]

Also, the above table shows that fNIRS depict balanced temporal and spatial resolution which stands as an added advantage for the selection of fNIRS over EEG and fMRI.

1.2 Problem Statement

The under developing countries cannot afford the cost of expensive fNIRS equipment due to which a researcher in such countries have to travel to another country where fNIRS equipment is available, to acquire data for conducting their research work in this emerging field of Bran Computer Interface.

1.3 Objectives

This research is focused onto developing a low cost fNIRS equipment with results match-able to already available multi channel wireless fNIRS systems to replace the expensive devices with the not only a cost-effective solution but still with the provision of being wore by an individual.

- Develop a 12 channel fNIRS equipment for the pre-frontal region
- Data Acquisition from the developed equipment
- Observe Human Brain activity for two different tasks
  (Mental arithmetic and Rest)
- Classification of brain activity with minimum effective criteria
  (*Considered to be atleast 70%*)

CHAPTER 2

Literature Review

2.1 Literature Review

This chapter elaborates in order of occurrences the developments of functional near infrared spectroscopy (fNIRS) equipment over the last two decades. The development of optical methods originated from the muscle oximeter invented by Glenn Millikan in the forties. It is well known that brain activity is associated with a number of physiological events; some of which are associated with changes in the optical properties of brain tissue, and can be assessed by optical techniques. The major advantages of optical methods include the biochemical specificity; temporal resolution in the millisecond range; the potential to measure intracellular/intravascular events simultaneously; and the ease with which devices can be transported.

The development of fNIRS instrumentation from 1992 *(single channel system with a low temporal resolution and poor sensitivity)* up to the multi-channel systems *(the first 10-channel system was introduced in 1995)* and the participation made in parallel to all this research by various companies for launching fNIRS devices commercially has been explained.

Typically an optical apparatus consists of a light source due to which the tissue emits light and this light is detected after interacting with brain tissues. Light tissue interaction is of two types namely: (a). absorption and b). scattering. The optical methods are developed from muscle oximeter that is used to monitor person's oxygen saturation. The brain tissue is responsible for all brain activities that can be detected by optical properties of brain tissue [4] -- [17].

Back in 1980, prototype NIRS instruments developed by Marco Ferrari, were used to measure the changes in brain oxygen level in animal models and human adults. Later in 1984, David Delpy developed several NIRS instruments to measure the oxygenation, hemodynamic and hemoglobin concentration level in sick newborn babies [18]. The first commercial system was built in 1989 by Hamamatsu photonics K.K forming the basis of single channel continuous wave (CW).

From 1980 to 1995, nine companies were involved in adding up towards NIRS prototypes [19]

1. American Edwards Laboratories in collaboration with Duke University.
2. Critikon and Johnson & Johnson with Zurich University.
3. Hitachi. Ltd. Central Research Laboratories
4. Near Infrared imaging Inc. with university of Pennsylvania
5. NIRS system, Inc. and Edward Life sciences Corp. with Johns Hopkins University.
6. Radiometer with Copenhagen university
7. Sclavo with "Instituto Superiore di Sanita"
8. Shimadzu with Hokkaido University.
9. Somanetics Corporation

Selection of the optical instrument mainly relied on the NIR light intensity, wavelength, age of the subject and surface area of head. Using the same concept, In 1990s, the first prototypes and some commercial two channel brain oximeters used to monitor the brain activities of adults and newborn were developed. The main purpose of developing such systems was to improve the clinical outcomes. First device approved by United States Food and Drug Administration in 1993 was focused onto determining the level of oxygen in cerebral region. Later on commercial single channel, spatialy resolved NIRS equipment got introduced in Japan. As the advancements went on, two channel oximeter commercialized in 1998. Overall, about 10,0000 oximeter devices were utilized mainly by adults all around the world for the betterment of the clinical world. [4] – [17]

fNIRS and fMRI usually measure the hemodynamic responses. In 1993, alongwith the development of two channel brain oximeters, five single channel instruments based on working principle of detecting specific changes in Oxygenated Hemoglobin (HbO) and deoxy Hemoglobin (HbR) during various mental tasks came into use. It was observed that fNIRS mapping depends upon the type of internal operations happening during mental tasks which can can be interpret by the light interference

between different channels. CW single channel prototype was developed for detecting reproducible motor-cortex oxygenation patterns.

Combination of data from different type of techniques, gives complete description of brain activities. The present high temporal resolution, multi-channel systems use three different NIR techniques and complex data acquisition. It gives multiple measurements and display results in graphical form for specific cortical area. Though up till now, 256 channel wearable and wireless systems that allows fNIRS measurements in daily activities has been made available commercially [4] – [29].

The gap lies there for the researchers of the under developing countries who cannot afford the cost of such expensive equipment and have to travel around the world just to acquire data for conducting their research work in this emerging field of Bran Computer Interface. Thus this research presents a low cost fNIRS equipment with matchable results to those of the wireless multi channel fNIRS systems to replace the expensive devices with the not only cost-effectiveness but still with the provision of being wore by an individual.

CHAPTER 3

fNIRS
Equipment Pre Fabrication

3.1 fNIRS Equipment Pre Fabrication

This chapter briefly explains components used for developing the fNIRS equipment and parameters being considered while selecting each component. Literature reveals that only near IR of wavelength between 630nm to 910nm can penetrate through human brain effectively to a distance of 3-4 cm [3]. The functional near infrared spectroscopy (fNIRS) equipment developed in this research therefore constitutes a specific arrangement of near infrared LEDs as source of input signal and at its counterpart photodiodes for acquiring the response. The specific arrangement refers to the area of brain under observation. This research being focused onto observing the human brain activity in the prefrontal region, the placement of emitters and detectors follows the following pattern.

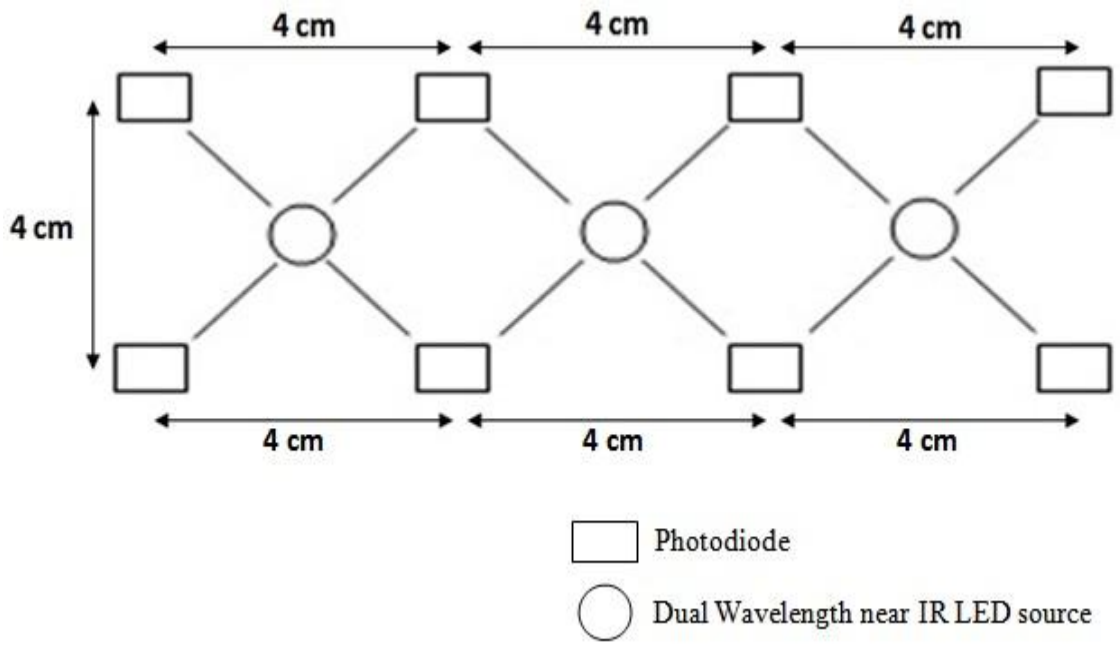

Figure 3.1: Placement of dual wavelength near IR LED sources and photodiodes for the fNIRS equipment. [3]

where 760 nm and 850 nm are the two wavelengths emitted by the dual wavelength near IR LED sources and the photodiodes have the sensitivity range between 320 nm

and 1100 nm. The LEDs are responsible for emitting near IR into the brain and the detectors respond to the reflected light from the brain [3].

The design of support circuitry for near IR LED sources and photodiodes involved consulting their respective datasheets. Near IR LED source used here consists of three terminals. Figure 3.2 shows the pin configuration of the near IR LED source.

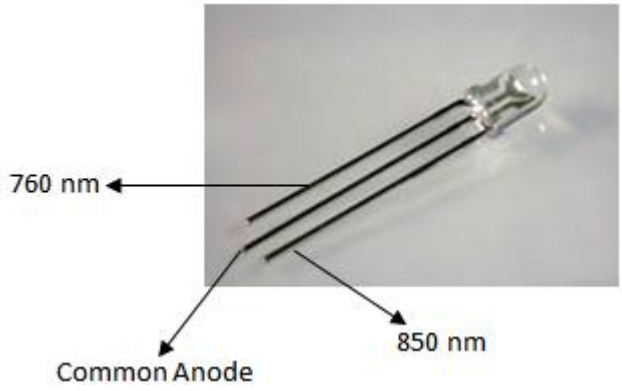

Figure 3.2: Pin Configuration of near IR LED source

A wavelength of 760 nm is emitted when a signal is sent to the smallest leg of the LED on the left. Similarly when signal is sent to the right most leg, wavelength of 850 nm is emitted. The center pin contains the anode of both the wavelengths and therefore is used to activate the LED for emitting either of the two wavelengths. This means a wavelength is not emitted until its common anode pin is activated.

An issue arises when two wavelengths are to be thrown from the near IR LED source. The two wavelengths cannot be thrown at the same time as we need to observe collected data separately for each wavelength to distinguish between at least two different brain activities. To achieve this a switching circuit needed to be designed that can toggle between 760 nm and 850 nm after regular intervals. A circuit using transistors and resistors formed the switching circuit ensuring that the current demand for each wavelength is fulfilled.

On the other hand photodiodes being used constitute of two legs. One being anode and the other is cathode. Figure 3.2 shows the pin configuration of photodiode. It

conducts in reverse biased and output of each photodiode is acquired across a resistor.

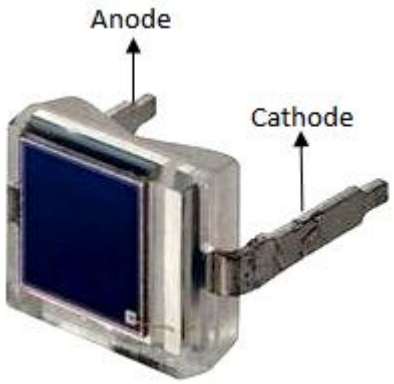

Figure 3.3: Pin Configuration of photodiode

It can be summarized that two major support circuits one for near IR LED sources and the other for photodiodes made the complete fNIRS equipment operative. Values for LEDs support circuit components that included transistors and resistors were calculated using knowledge of basic electronics.

Components of calculated values were tested first on breadboard to confirm the current ratings and the switching between the two wavelengths. Similarly, components of support circuitry for photodiodes were tested on breadboard. Response of photodiodes

CHAPTER 4

Fabrication, Data Acquisition & Signal Processing

4.1 Fabrication

Components finalized after observations were once again used with the complete support circuit on breadboard. Though LED switching and the response of photodiode in presence of light and in case of dark showed appropriate behavior but the reliability of the device needed the support circuitry of the LEDs and photodiodes to be shifted to a printed circuit board (PCB). This demand of PCB had the intention of keeping minimum wires open to avoid disconnections and untidy troubleshooting in case of sorting out an issue.

PCB layout of the complete device including 3 near IR dual wavelength LEDs, its support circuit, 8 photodiodes, its support circuit and the power regulation circuit has been designed in Proteus. The very first prototype in the etched form on a standard copper board can be seen in the figure below.

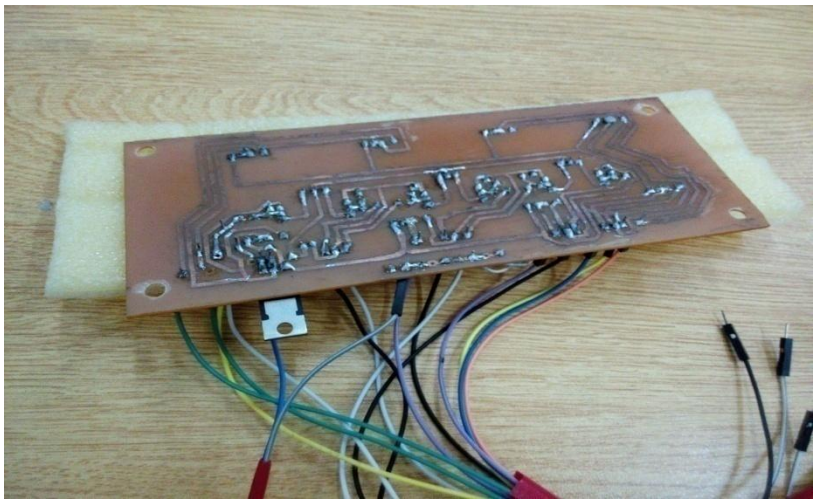

Figure 4.1: First prototype of fNIRS equipment on a non flexible PCB

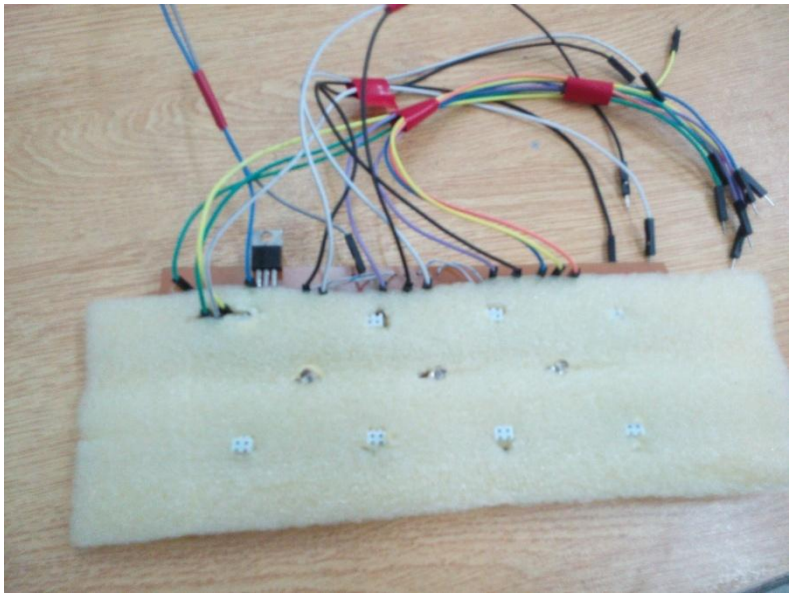

Figure 4.2: Protective material covering first prototype of fNIRS equipment

All tests as being done on breadboard such as switching of LEDs, voltage drops at test points and response of photodiodes in darkness and light were verified. Results were satisfactory and the prototype has been made ready for taking readings. The standard procedure of making observations from a device for pre frontal cortex can be seen below.

It can be seen above that the fNIRS equipment being wore by a participant under study has to bend as per the shape of the brain to make complete contact. But, PCB developed at present couldn't be used as it is since it cannot bend along with the curvature of a human forehead that varies from person to person. Therefore, a second prototype with a flexible PCB replaced the first prototype using the same PCB layout. It can be seen below

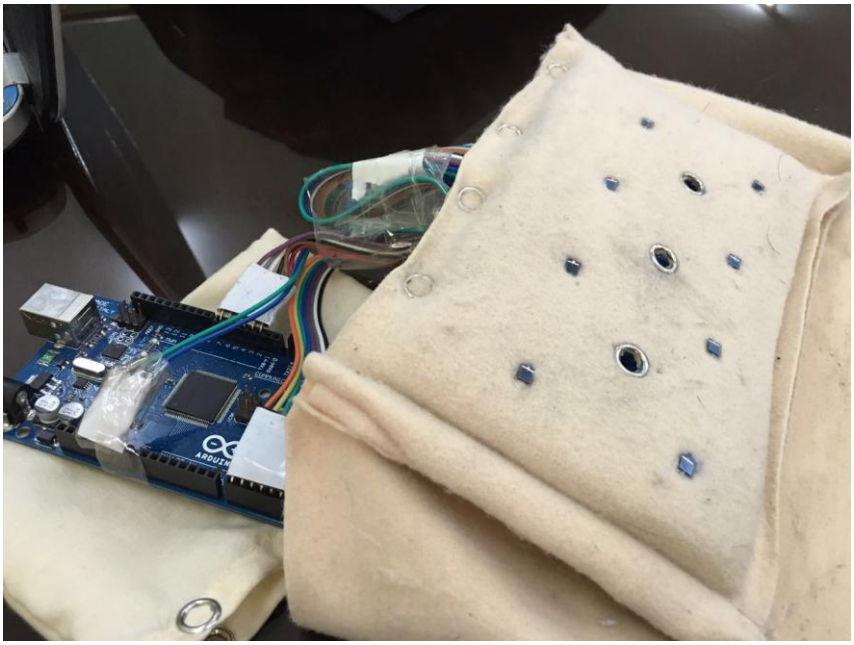

Figure 4.3: fNIRS equipment sensor band for wearing on forehead

Figure 4.4: fNIRS equipment connected with Matlab GUI through arduino

In this way only the input and output wires were kept open.

4.2 Data Acquisition

LEDs switching and response of photodiodes has been captured through arduino and analyzed using MATLAB. The sequence of Signal Acquisition and its processing has been chalked out in the following flow chart.

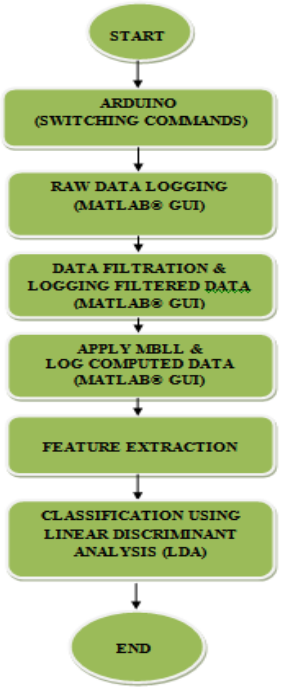

Figure 4.5: Sequence of Signal Acquisition and its processing in a flow chart

It would be significant to mention here that flow chart in the figure above has been developed in accordance with a conventional brain computer interface. Each stage of the conventional system is replaced with an equivalent phase of research.

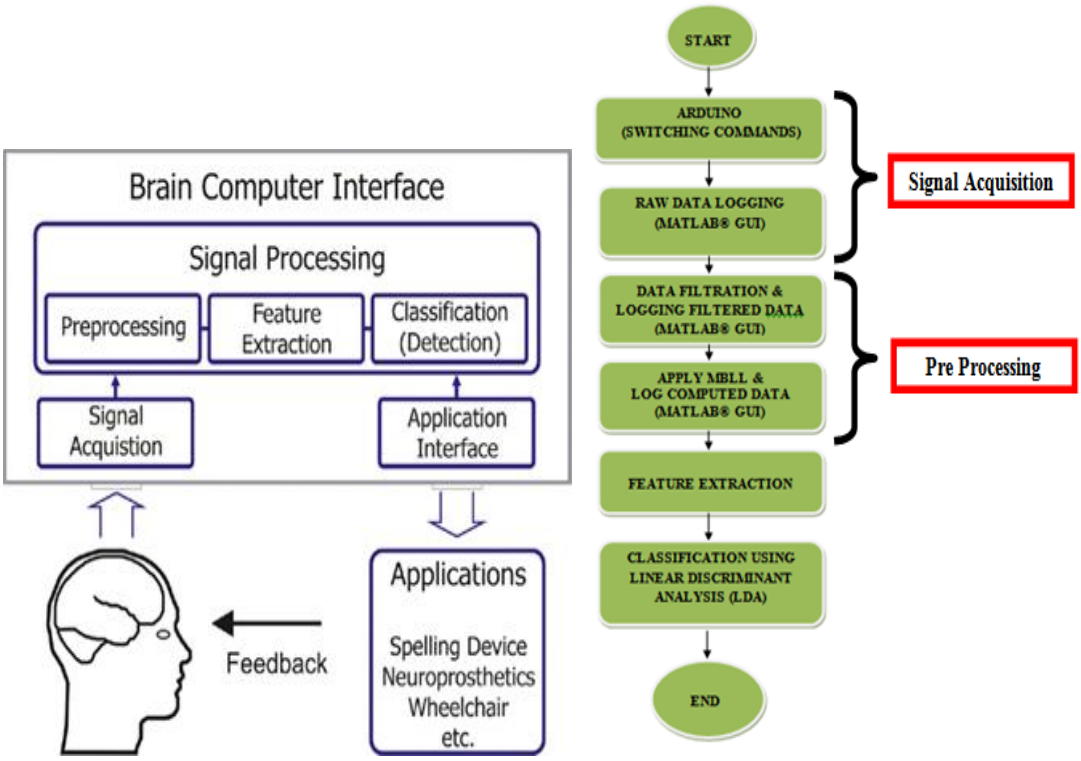

Figure 4.6: Comparison between a conventional BCI with the modified BCI system of the present research

Signal acquisition phase is till logging of data in form of intensities. Pre processing phase involves application of filter for removing undesired noise and conversion of intensities of dual wavelength to change in concentration of two chromophores HbO and HbR at instants of time being logged.

4.2.1 Signal Acquisition

In signal acquisition phase a participant wore the developed fNIRS equipment and the near IR LED sources were continuously switched between the two wavelengths through the digital pins of Arduino.

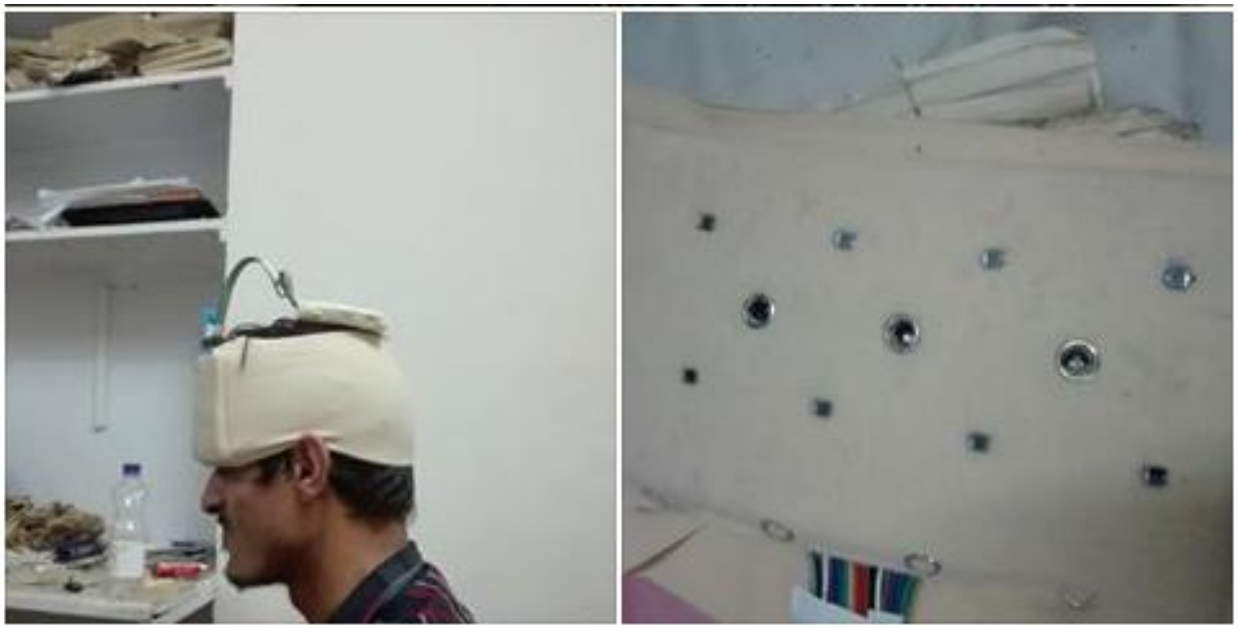

Figure 4.7: Participant wearing the developed fNIRS equipment

Response of the reflected light from brain tissues has been captured at each of the eight photodiodes and is continuously logged in an excel file through MATLAB. For this purpose a MATLAB GUI was developed to view the signals at each channel at runtime against both the wavelengths. Initially intensities were plotted against each photodiode on the following GUI in MATLAB.

Figure 4.8: fNIRS equipment Graphical User Interface (GUI)

Each tab in the GUI given above perform a specific function. In signal acquisition phase four tabs were used

1) Connect
2) File Path
3) Receive Data
4) Stop Receiving

"Connect" tab establishes the connection of arduino with the fNIRS equipment when pressed after selecting the baud rate and giving the file path for storing the data sets. Data was received using "Receive Data" tab and values are continuously logged into an excel file and saved at the file path mentioned unless "Stop Receiving" tab is pressed.

Now "Stop Receiving" tab cannot be pressed at any stage since a standard has to be defined for keeping the experimental values consistent for comparison. An experimental paradigm has to be defined to conduct these experiments. To verify the working of the device it was aimed to collect data for two different tasks and hence in this research experimental paradigm being considered has been mentioned in the table below.

Mental Arithmetic **30 seconds**	**Select a 3 digit number** **Apply DMAS with numbers 2,3,4 & 5 respectively**
Rest 30 seconds	Relax your mind. Stop performing the mental arithmetic task

Table 4.1: Experimental Paradigm of the research

Thus whenever 30 seconds have passed after pressing the “Receive” tab, “Stop Receiving” is pressed and the logging of data is being cut off though the device is still on participant forehead.

4.2.2 Pre Processing

In the pre processing phase, remaining tabs “Apply Filter” and “Apply MBLL” have been used. The filter being used is a low pass filter with cut off frequency of 0.3 Hz [3]. The stored data in excel file is passed through this filter right data logging is stopped. This filter removes the noise that can be caused by heartbeat and respiratory motions of humans.

After application of filter, filtered values are ready to be passed through the Modified Beer Lambert Law (MBLL). Until now the intensities being filtered cannot be of any help to depict the brain activity being performed. It cannot be yet differentiated between the two activities mentioned in the table above until some the intensities can be converted into some numerical values based on the behaviour of the brain.

Among various brain chromophores like oxy-hemoglobin (HbO), deoxy-hemoglobin (HbR), water, lipids etc, it is important to identify the chromophores that need to be observed. Identification is based on the absorption response of brain chromophores subject to different wavelengths being used. The dual wavelength near infrared LEDs being used, emit wavelengths of 760 nm and 850 nm. It can be seen from figure 1.7, that in this range only the oxygenated hemoglobin (HbO) and the deoxygenated hemoglobin (HbR) *(also termed as reduced hemoglobin)* are the two chromophores showing significant absorption and therefore are supposed to contain the information of the brain activity being performed. Thus, HbO and HbR absorb light of near infrared region better than the rest [3].

The purpose of using two wavelengths relates to two unknown variables HbO and HbR. The conversion of intensities to changes in concentration of Hbo and HbR is done using Modified Beer Lambert Law. Modified Beer Lambert Law has been deduced from Beer Lambert Law as it is also related to dealing with intensities.

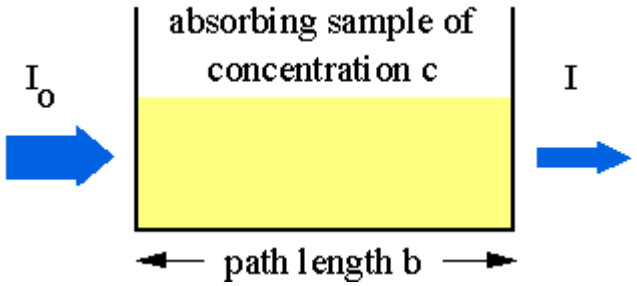

Figure 4.9: Beer Lambert Law phenomenon

It is applicable for cases of non scattering medium and relates the input and output with the following equation.

$$I_{out}(t) = I_{in} e^{-\mu_a(t)\times l} \qquad \text{..... (4.1)}$$

where

$I_{out}(t), I_{in}(t)$: Intensities o f the detected and incident lights

$\mu_a(t)$: Absorption coefficient of the medium

l : Distance between the source and the detector

Taking natural log on both sides, the above equation becomes

$$-\ln \frac{I_{out}(t;\lambda)}{I_{in}(\lambda)} = \mu_a(t;\lambda)\times l. \qquad \text{..... (4.2)}$$

Here, left side of the equation is termed as absorbance (or optical density) A [unitless]. It depends on the wavelength λ [nm] of the incident light. Hence, equation 4.2 can also be written as

$$A(t;\lambda) = -\ln \frac{I_{out}(t;\lambda)}{I_{in}(\lambda)} \overset{\Delta}{=} \mu_a(t;\lambda)\times l \qquad \text{..... (4.3)}$$

Thus, Beer Lambert Law gives a linear relationship between absorbance and concentration of a compound at a fixed wavelength. The need of modification came up from the fact that the human brain does not compose of the non scattering tissues[]. Due to this scattering phenomenon, the path length factor cannot remain a straight line and therefore it cannot be represented by l alone. It has been observed

that in scattering mediums that the profile of light from source to detector forms a banana shape as shown in figure below.

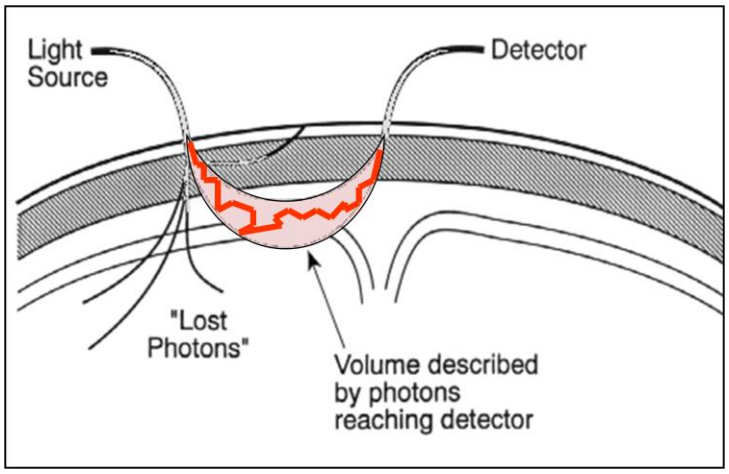

Figure 4.10: Profile followed by near infrared LED source till the detector in a scattering medium [3]

Thus equation 4.3 formed from Beer Lambert Law for non scattering mediums can be modified with a few assumptions to develop Modified Beer Lambert Law. The assumptions are:

1) The absorption of the tissue changes homogeneously
2) The scattering lost is constant

Equation 4.3 now becomes

$$A(t;\lambda) = \mu_a(t;\lambda) \times l \times d(\lambda) + \eta \qquad \text{.....} \quad (4.4)$$

where

$d(\lambda)$: Differential path length factor

η: Unknown geometry-dependent factor (represents intensity lost caused by scattering)

Since change in concentration is being used at every instant so the intensity loss (η) for each case remains negligible and therefore can be assumed zero in equation 4.4. So the above equation can be written as:

$$\Delta A(t;\lambda) = A(t_2;\lambda) - A(t_1;\lambda) = -\ln \frac{I_{out}(t_2;\lambda)}{I_{out}(t_1;\lambda)} = \Delta\mu_a(t;\lambda) \times l \times d(\lambda) \quad \text{.....} \quad (4.5)$$

$A(t_1;\lambda), A(t_2;\lambda)$: the absorbances measured at two points

$I_{out}(t_1;\lambda), I_{out}(t_2;\lambda)$: the intensities of detected light at two points

As explained earlier that the brain tissue chromophores HbO and HbR respond significantly to near infrared light at 760 nm and 850 nm wavelength, therefore, we get

$$\Delta\mu_a(t;\lambda) = \left[\alpha_{HbO}(\lambda)\Delta c_{HbO}(t) + \alpha_{HbR}(\lambda)\Delta c_{HbR}(t)\right] \quad \ldots\ldots \quad (4.6)$$

where

$\alpha_{HbO}(\lambda), \alpha_{HbR}(\lambda)$: the extinction coefficients of HbO and HbR, respectively [$\mu M^{-1}\text{cm}^{-1}$]

$\Delta c_{HbO}(t), \Delta c_{HbR}(t)$: the concentration changes of HbO and HbR, respectively [μM]

Using value of $\Delta\mu_a(t;\lambda)$ in equation 4.5 it can be rewritten as

$$\Delta A(t;\lambda) = \left[\alpha_{HbO}(\lambda)\Delta c_{HbO}(t) + \alpha_{HbR}(\lambda)\Delta c_{HbR}(t)\right] \times l \times d(\lambda) \quad \ldots\ldots \quad (4.7)$$

Since two wavelengths 760 nm and 850 nm are being used in present research so equation 4.7 can be exclusively developed for each wavelength. Thus, by measuring the absorbance at two wavelength, λ_1 and λ_2 (assume that d is constant) following two equations are developed.

$$\Delta A(t;\lambda_1) = \left[\alpha_{HbO}(\lambda_1)\Delta c_{HbO}(t) + \alpha_{HbR}(\lambda_1)\Delta c_{HbR}(t)\right] \times l \times d \quad \ldots\ldots \quad (4.8)$$

$$\Delta A(t;\lambda_2) = \left[\alpha_{HbO}(\lambda_2)\Delta c_{HbO}(t) + \alpha_{HbR}(\lambda_2)\Delta c_{HbR}(t)\right] \times l \times d \quad \ldots\ldots \quad (4.9)$$

By rearranging the equations 4.8 and 4.9 for acquiring change in concentrations of HbO and HbR

$$\begin{bmatrix}\Delta c_{HbO}(t)\\ \Delta c_{HbR}(t)\end{bmatrix} = \frac{\begin{bmatrix}\alpha_{HbO}(\lambda_1) & \alpha_{HbR}(\lambda_1)\\ \alpha_{HbO}(\lambda_2) & \alpha_{HbR}(\lambda_2)\end{bmatrix}^{-1}\begin{bmatrix}\Delta A(t;\lambda_1)\\ \Delta A(t;\lambda_2)\end{bmatrix}}{l \times d}. \quad \ldots\ldots \quad (4.10)$$

These two equations of Modified Beer Lambert Law can therefore be used and solved for obtaining the values of the two chromophores HbO and HbR against each brain activity in terms of change in concentration of HbO and HbR.

Until now data acquisition, data logging, data filtration and application of MBLL has been carried out at runtime. It may be noted that everytime a filter is applied and whenever values are passed onto MBLL all resulting values are continuously stored in the same excel file that initially contained the intensities of reflected near IR light of the two wavelengths.

So after filtration and conversion of intensities to change in concentration of HbO and HbR using MBLL *(equations embedded at the back of GUI)* the system is made to go offline and values of change in concentration of both the chromophores are taken from the excel file for analsis in offline mode.

4.3 Signal Processing

4.3.1 Feature Extraction & Classification

Usually two or more signals are either differentiated on basis of signal pattern or range of occurrence of the signals but when dealing with cases that involve brain computer interface (BCI) signals don't follow a single pattern and their range of occurrence is not fixed. Process of feature extraction is necessary for such cases to differentiate two or more signals from each other.

Work being done in this domain refers that feature extraction can be done using two common techniques that include:

- Heuristic Methods
- Genetic Algorithm

Amongst these, genetic algorithm is applicable to cases involving thousands of data sets. In cases where data sets are not in great number, selected feature or a combination of features extracted by genetic algorithm for distinguishing two or

more tasks from each other might not give good results. As per experimental paradigm defined in this research data samples between 150 and 160 are acquired for each task.

In contrast to using genetic algorithm, heuristic methods are advised to be the simplest way for extracting features from two or more data sets with less number of samples. Heuristic methods suggest to calculate the mean, peak, slope, variance, kurtosis, skewness etc. of the data set either spatially or temporally. After calculating so, use each feature individually and pass the data sets through a classifier to see if the classification accuracy is above the minimum effective criteria of 70% [3]. If the classification accuracy comes out to be above the minimum effective criteria, the selected feature is a right choice for distinguishing the two tasks else check for each individual feature the classification accuracy and even if this does not come up meeting the desired criteria try using a combination of features. Any classifier Principal Component Analysis (PCA), Linear Discriminant Analysis (LDA), Support Vector Machine (SVM), Artificial Neural Networks (ANN) etc can be used to differentiate two or more tasks.

In light of above description, heuristic methods have been used for feature extraction in this research. Spatial Mean of the data sets when passed through Linear Discriminant Analysis (LDA) well passed the minimum effective criteria of 70%. Results of ten participants with single trial sessions conducted according to experimental paradigm mentioned above has been shown in tabular form.

Participants	Accuracy (Feature Mean)
Participant 1	84.03%
Participant 2	76.08 %
Participant 3	65.21 %
Participant 4	80.38%
Participant 5	74.23 %
Participant 6	72.25 %
Participant 7	81.25 %
Participant 8	75.44 %
Participant 9	69.52 %
Participant 10	67.12 %

Table 4.2: Classification accuracy from single trial of ten participants

Average accuracy of 74.55 % ± 9.48% has been observed amongst single trial sessions conducted with 10 participants.

CHAPTER 5

Conclusions & Recommendations

5.1 Conclusion

A cost effective functional near infrared spectroscopy (fNIRS) equipment has been developed successfully for monitoring human brain activity in the pre frontal cortex region. Data acquired is continuously logged into an excel file and the intensities passed through Modified Beer Lambert Law (MBLL) are being converted into change in concentration of HbO and HbR according to human brain activity corresponding to each task defined in experimental paradigm. Feature extraction revealed spatial mean alone to be an optimal feature for the present case suggesting that a combination of features is not always to be considered. Linear Discriminant Analysis (LDA) showed the average classification accuracy to be 74.55 % ± 9.48% against a single trial session of 10 participants validating the obtained results to be well above the minimum effective criteria of 70%. Thus the developed fNIRS equipment can be used as reliable equipment for monitoring Human Brain Activity within Pakistan instead of going to various universities outside Pakistan just for acquiring data as per desired experimental paradigm.

5.2 Future Recommendations

As future recommendation the developed fNIRS equipment can be used for rehabilitation purposes. It can be used to observe the state of stress due to work load or fatigue on a human brain. The use of this equipment can be extended to observe emotions or feeling of happiness and sadness in one's personality. Paralyzed people can be trained to perform some basic tasks on their own using this piece of equipment. Improvements like casing and beautification can be done to brought up the prototype to a finished product that be made available to researchers working in different universities of Pakistan in this field.

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